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TRANSLATION

DEFORMATION AND THE ROLE OF THE TEMPERATURE FACTOR IN THE PROCESS OF CUTTING OF TITANIUM ALLOYS

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DEFORMATION AND THE ROLE OF THE TEMPERATURE FACTOR IN THE PROCESS OF CUTTING OF TITANIUM ALLOYS.

by

Engineer A. D. Chubarov and Engineer N. N. Novikov.

In recent years titanium alloys have been put to wide use as construction materials for machine parts which must possess a high fatigue strength.

The physical and mechanical properties of the surface layer remaining after the metal has been machined with a cutting tool exert the principal influence on the fatigue strength of titanium alloys. This calls for a study of the deformations arising in the surface layers of the above-mentioned alloys in the cutting process, since the modern concept of cutting is that of a process of elastic-plastic deformation [1].

It is, therefore, important to examine the deformations affecting the removed layer (chips) and the one remaining in the material under the machined surface. The strain in the removed layer, which may, to a certain extent, be characterized by the shrinkage of the chip, has been examined in a separate study [2]. The present article deals with the results of an investigation of deformation of the layer under the machined surface*).

Strain hardening is the chief result of plastic deformation and the temperature-velocity factor in the process of cutting [1], [3].

According to the laws of solid state physics, in the process of plastic deformation, along with strain hardening (strengthening) there also develops a counter process, that of recovery, which represents a reduction or partial

*) The investigation was carried out by the authors under the guidance of Doctor of Technical Sciences Professor V. A. Krivoukhov.

removal of strength and hardness. The recovery phenomenon is manifested starting from a definite temperature for each metal.

Similar phenomena occur in the process of cutting alloys based on nickel and iron.

As to titanium alloys, such a concept of the processes which occur when they are cut and which cause strain hardening is incomplete, since the nature of the phenomena involved is somewhat different in this case.

Information available in published sources on the hardening of surface layers in titanium alloys in the process of cutting is very scarce. Hence the objective of this study was, first, to compare the hardening of titanium alloys with the strain hardening of alloys based on nickel and iron depending on the cutting parameters in different types of machining. Secondly, the aim was to determine the characteristics of hardening in the layer under the machined surface during the cutting of titanium alloys.

The investigation was carried out with the domestic titanium alloys VT2, VT3, VT3-1, and VT5, as well as (for purposes of comparison) with the heat-resistant alloys nickel-based EI-437 and EI-617, and the alloys based on iron and 45 steel 30KhGSa, 18KhNVA, and ShKh15.

The conditions of cutting described in Tables 1 and 2 were sele[illegible] in accordance with the recommendations contained in reference sources and on the basis of production experience. Moreover, the cutting tool was fitted with plates made of hard VK8 alloys (for rough finishing and intermittent cutting) and VK2 (for finishing work). These plates have a higher wear resistance than those made of the hard VK4 alloy.

The depth and the degree of hardening (strain hardening) were determined by the method of X-ray diffraction analysis. This is the best of the existing methods in application to titanium alloys, because of the characteristic inhomogeneity of the mechanical properties of their structural components (the transformed β-phase and primary α-phase) and the possible presence of

intermetallic-phase inclusions. In addition to this, for purposes of compariison, strain hardening was also determined by the microhardness measurement method from oblique microsections with a PMT-3 instrument.

Table 1.

Depth and Degree of Strain Hardening Resulting from Different Types of Titanium Alloy Machining.

Type of Machining	Magnitude of the investigated cutting parameter.	Depth of strain h, in mm.	Degree of hardening N in %	Other cutting parameters
Turning	v = 10 m/min	0.160	127	s = 0.11 mm/rev.
	" = 30 "	0.130	118	t = 1.0 mm
	" = 50 "	0.125	114	$\delta_3 \leq 0.1$ mm
	" = 70 "	0.100	110	
	" = 100 "	0.090	108	
	s = 0.09 mm/rev.	0.060	112	
	" = 0.11 "	0.090	118	v = 40 m/min.
	" = 0.14 "	0.120	122	t = 1.0 mm
	" = 0.35 "	0.165	129	$\delta_3 \leq 0.1$ "
	" = 0.45 "	0.210	137	
	t = 0.5 mm	0.110	121	v = 40 m/min.
	" = 0.7 "	0.120	123	s = 0.22 mm/rev.
	" = 1.0 "	0.115	123	$\delta_3 \leq 0.1$ mm
	" = 2.0 "	0.125	125	
	$_3$ = 0.18 mm	0.112	123	
	" = 0.30 "	0.13	127	v = 40 m/min
	" = 0.31 "	0.15	128	s = 0.22 mm/rev.
	" = 0.44 "	0.18	132	t = 1.0 mm
	" = 0.58 "	0.21	140	
	" = 0.9 "	0.25	145	
Line Milling	v = 12 m/min	0.26	142	s_z = 1.5 mm/tooth t = 1.0 mm
Surface Grinding	t = 0.05 mm " = 0.10 "	0.04 0.06	130 125	v_{kp} = 30 m/sec v_u = 8 m/min s_n = 2 mm/doub. turn.
Hand Polishing	v_{kp} = 30 m/sec	0.04	114	Material of disk - felt. Abrasive powder EB80 on glue.

NOTE: Cutting was carried out without cooling.

Table 2.

Comparison of Strain Hardening Intensity During the Grinding of Alloys Based on Titanium, Nickel, and Iron.

Investigated Material	Depth of strain hardening h in mm.	Degree of strain hardening N in %
Alloy VT3	0.04	130
" EI617	0.06	117
" EI437	0.08	119
Steel 30KhGSA	0.08	124
" 18KhNVA	0.08	121
" ShKh15	0.06	117
" 45	0.08	117

Machining conditions: v_{cr} = 30 m/sec; v_d = 8 m/min; t = 0.05 mm; cross-feed; s_n = 2 mm/double-wheel turn (alloy VT3); s_n = 12 mm/double-wheel turn (other materials).

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Fig. 1. Depth and degree of strain hardening as functions of the cutting speed, feed, depth of cutting, and wear of the cutter along its rear surface during turning of a titanium alloy.

(1) Depth of work-hardened layer; (2) width of K_α doublet line and degree of strain hardening; (3) Degree of strain hardening; (4) Width of K_α doublet line; (5) Depth of work-hardened layer.

To reduce the effect of accidental errors on the final results, the arithmetic mean of three measurements for X-ray diffraction analysis, and five imprints at each level of the oblique section were taken in determining strain hardness by the microhardness method.

Experimental data obtained in the process of machining titanium alloys by turning show that the cutting parameters exert a varying effect on the hardening of these alloys (Fig. 1). A sharp decline in hardening occurs as the cutting speed increases to 50-60 m/min; the variation thereafter is insignificant. This agrees closely with the nature of variation in chip shrinkage [2]. Hardening increases with increase in feed, but it increases only slightly in relation to depth of cutting. A steady growth in hardening is observed with increasing wear along the rear surface of the bit δ_3 (over the investigated range).

Materials possessing higher plasticity are known to undergo a relatively high degree of hardening as a result of cutting. The alloys based on titanium are characterized by lower plasticity as compared with those based on nickel and iron. This is indicated by the results of tests of the plastic compression of specimens carried out by the authors.

As may be seen from comparison of the curves (Fig. 2), the polytropic index of plastic compression m, which represents the slope of the rectilinear section of the curves, is smaller for titanium alloys.

The smaller value of the polytropic index of plastic compression, in fact, characterizes a material possessing lower plastic properties.

Consequently, it would have been reasonable to expect that in the cutting of titanium alloys the hardening in the layer underlying the machined surface would be less than the work-hardening in alloys based on nickel and iron.

However, this is not substantiated by the results of investigations carried out with a view toward determining the depth and intensity of hardening in relation to the cutting parameters (see Fig. 1) and to the various types

of machining (see Tables 1 and 2).

A comparison of the hardening of titanium alloys as a result of turning (according to the authors' data, Table 1) with strain hardening of alloys based on nickel (according to the data of [5]), as well as comparison of the results obtained upon the hardening of alloys based on titanium, nickel, and iron in the process of grinding (see Table 2), reveal the following.

The most characteristic feature of the alloys based on titanium consists of the fact that the intensity of their hardening in consequence of machining is considerably higher than is the case for the other alloys under consideration.

In the process of turning and milling of titanium alloys one should expect a drop in hardening to occur when the cutting speed $v = 50$ m/min is attained and the temperature in the strained zone assumes a considerable value (above 600°). In the case of grinding this should take place when the melting point is reached [4].

However, as may be seen from the analysis cited, this does not occur in titanium alloys machined under normal atmospheric conditions. This fact is attributable to the somewhat different nature of the hardening.

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Fig. 2. Curves of plastic compression of alloys based on titanium, nickel, and iron.
(1) Load; (2) Alloy VT2, $m = 0.9$, $\sigma_0 = 141$ kg/mm^2 (3) Steel 30KhGSA; (4) Alloy EI617; (5) Remaining height of the specimen.

As was established by comparative cutting of titanium alloys under normal atmospheric conditions and in the neutral medium of argon, the peculiar nature of their hardening is due to the characteristic property of titanium of absorbing nitrogen, and especially oxygen, energetically at the corresponding temperatures (from 600° upwards) which occur during cutting.

Experiments in comparative cutting were carried out in a specially constructed apparatus, in accordance with a procedure described in a previously published paper [2].

It was established as a result of this investigation that the gases absorbed from the atmosphere cause embrittlement of the machined surface to a certain depth. This occasions an additional increase in hardness, which latter comes as a result of plastic deformation in the process of cutting.

This additional hardness acquired in consequence of the physical and chemical process exceeds considerably the decline in hardening caused by the temperature-velocity factor.

Thus, in the process of cutting of titanium alloys, hardening is a result of two phenomena: the strain hardening which occurs during plastic deformation and usually accompanies the process of metal cutting, and the embrittlement caused by the development of the physicochemical process of absorption of atmospheric gases by the titanium.

The theses indicated are well substantiated by curves (Fig. 3) plotted on the basis of the experimental data (Table 3). The curves characterize the nature and magnitude of hardening of the surface layer of a titanium alloy after cutting in ambient atmosphere conditions and in the neutral medium of argon.

The material investigated was the VT3-1; the hard VK2 alloy was used for the cutting point. The cutting conditions were: v = 200 m/min, s = 0.22 mm/rev., t = 1 mm.; no cooling was used in the process. Depth of work hardening: 0.1 mm; degree of work hardening: 121% in argon, 145% in the ambient atmosphere.

Table 3.

Results of Microhardness Investigation in Cutting of the VT3-1 Titanium Alloy by a Hard-alloy VK2 Cutting Tool

(v = 200 m/min; s = 0.22 mm/rev; t = 1 mm).

Depth of work hardening in mm.	Machining under atmospheric conditions		Machining in neutral medium of argon	
	Diagonal of the replica (average of five measurements).	Microhardness in kg/mm^2	Diagonal of the replica (average of five measurements).	Microhardness in kg/mm^2
0.0000	67.0	417.6	73.0	351.8
0.0013	71.0	371.9	74.3	339.3
0.0026	72.0	361.6	-	-
0.0039	-	-	74.8	335.0
0.0052	73.3	348.9	75.3	330.6
0.0066	74.0	342.3	76.6	319.5
0.0079	-	-	75.5	328.9
0.0092	74.0	342.3	-	-
0.0100	73.3	348.9	76.3	322.0
0.0118	73.5	347.0	76.7	318.6
0.0131	73.1	350.0	76.7	318.6
0.0144	73.3	348.9	77.3	314.8
0.0157	72.6	355.7	77.7	310.5
0.0183	74.6	336.8	78.3	305.8
0.0209	76.3	322.0	78.3	305.8
0.0236	76.0	324.5	78.0	308.1
0.0262	74.3	339.6	79.0	300.5
0.0314	75.6	328.0	79.0	300.5
0.0367	75.0	333.3	79.6	295.8
0.0393	74.6	339.7	79.6	295.8
0.0419	75.6	333.0	80.0	292.9
0.0472	77.3	313.7	79.7	295.1
0.0524	79.0	300.4	80.0	292.9
0.0655	80.0	292.9	80.3	290.7
0.0786	80.0	292.9	80.3	290.7
0.1048	80.6	288.5	80.6	288.5

A comparison of the curves confirms the considerations advanced above. The hardening of the surface layer of the VT3-1 titanium alloy resulting from cutting in the argon medium, which excludes the influence of the atmospheric gases, is a consequence only of plastic deformation and the temperature-velocity factor and constitutes work hardening. The depth of work hardening penetration under these cutting conditions reaches 0.1 mm, the maximum microhardness 351.8 kg/mm^2, and the intensity curve is smooth in nature.

As compared with the above, the graph representing the hardening of the surface layer after cutting under normal atmospheric conditions is somewhat different in nature. For the same depth of work hardening there is a clearly expressed zone (up to 0.05 mm) of increased microhardness which reaches 417.6 kg/mm^2 on the surface. The intensity of hardening is here sharply defined and uneven in nature. This attests to the occurrence of additional embrittlement under the influence of the physicochemical process of absorption of the atmospheric gases (nitrogen, and particularly oxygen). The temperature field of the zone of increased microhardness is quite adequate for development of the physicochemical process in question. On the machined surface the temperature exceeds 1000°, it is no lower than 500° at a depth of 0.025 mm, and at 0.05 mm it is 320 to 350° *). As may be seen from the graphs, the difference in microhardness after cutting in the ambient atmosphere and in the argon medium begins to level out after the depth of 0.05 mm is passed. This attests to termination of the process of embrittlement and to the effect of plastic deformation alone.

Thus, the investigations conducted on comparative cutting of titanium alloys under normal conditions and in a neutral argon medium permitted establishment of the phenomenon of embrittlement of the surface layer as a result of

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*) The temperature data were taken from experimental investigations and have been corroborated by analytical computation.

machining under normal atmospheric conditions. Moreover, this embrittlement is characterized by considerable unevenness (see Fig. 3).

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Fig. 3. Variation of microhardness of surface layer in depth after cutting of titanium alloys under atmospheric conditions (curve 1) and in a neutral medium (curve 2).
(1) Microhardness.

To assure a stable fatigue strength of parts made of titanium alloys which work under high vibration loads, in selection of the machining method and cutting parameters allowance should be made for hardening (see Fig. 1), so as to exclude a possible saturation of the machined surface with atmospheric gases (for example, the metal should be worked in a neutral medium or in vacuo) and to obviate the formation of embrittlement foci serving as centers of concentrated stresses of a special kind. For this purpose it is possible to apply intensive cooling of the cutting zone (for example, by using liquid CO_2).

At the same time, it must be noted that in order to reduce the magnitude of hardening of parts made of titanium alloys, turning should, whenever possible, be given preference over milling (see Table 1). The following may be said with respect to polishing and grinding. On the one hand, polishing has no advantages over grinding, since the depth of work hardening in both types of machining is practically the same. On the other hand, polishing is preferable since the degree of work hardening resulting from polishing is much lower than in grinding. Hence, polishing should be a compulsory finishing

operation in the manufacture of thin-walled parts for which high fatigue strength is a required condition. Grinding as a finishing operation may be employed only for such titanium alloy parts the service conditions of which permit an increased degree of strain hardening.

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